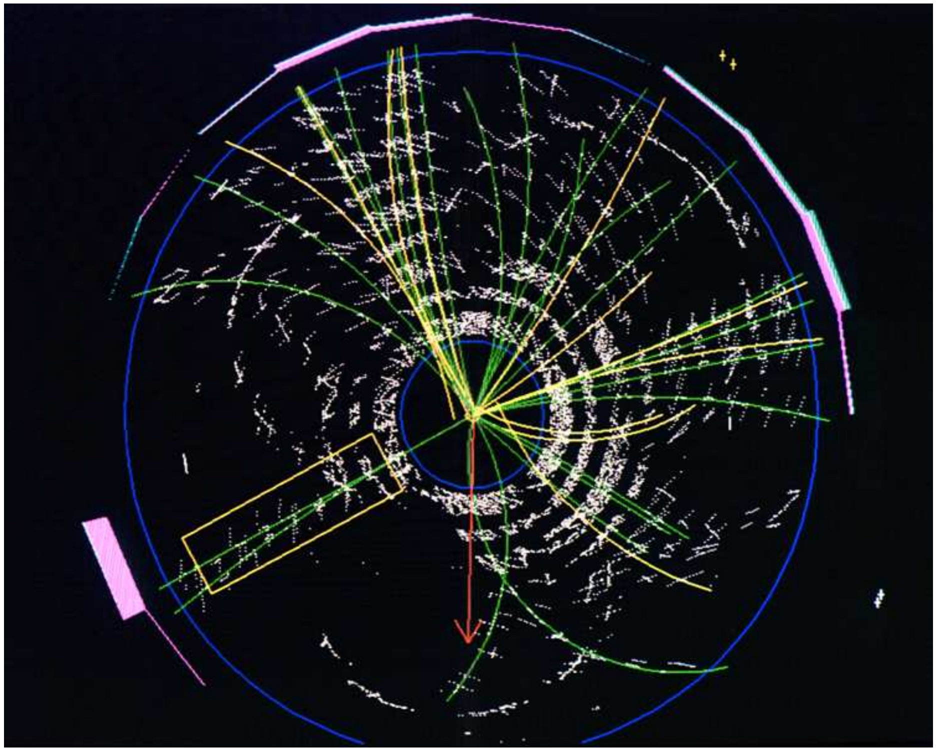
SEARCHES FOR STANDARD MODEL HIGGS BOSON AT THE TEVATRON

Bárbara Álvarez González

Universidad de Oviedo

Prueba de Suficiencia Investigadora,
Octubre, 2007



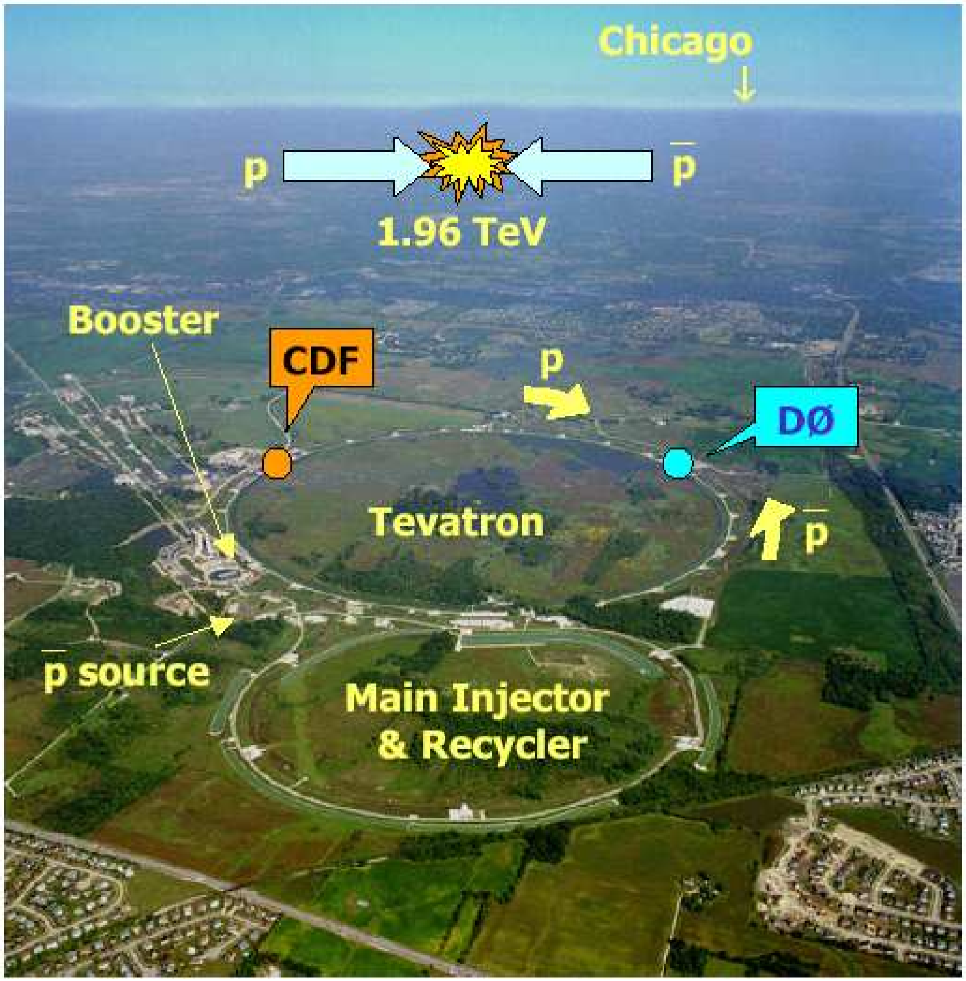
CDF Top Event in 1995 on Computer Screen

Outline

- Tevatron.
- CDF Detector.
- Motivation of the Higgs Search at Tevatron.
- Matrix Element Analysis.
  - ◇ Application of the method to Single top search.
- Conclusions.

Tevatron

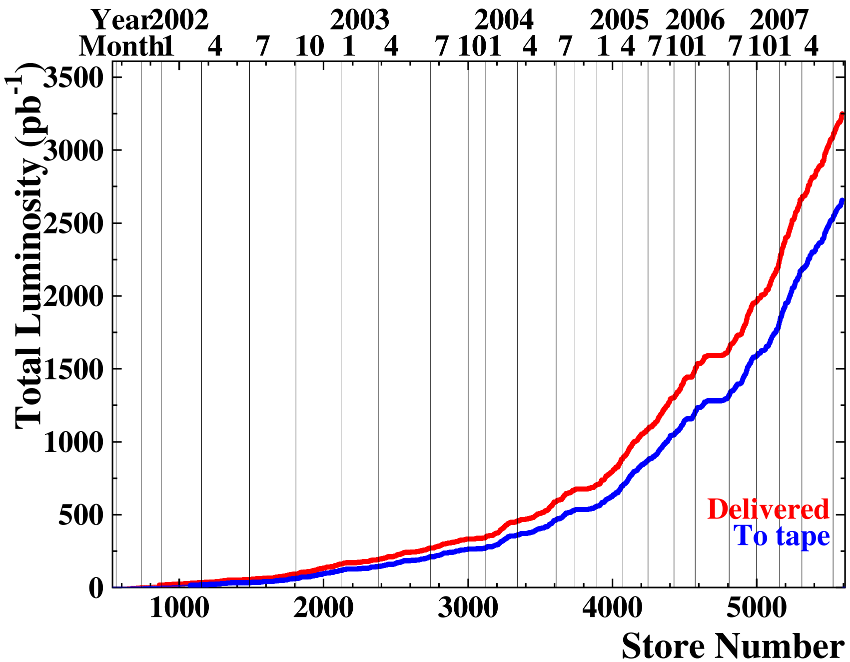
- The world's highest-energy particle accelerator.



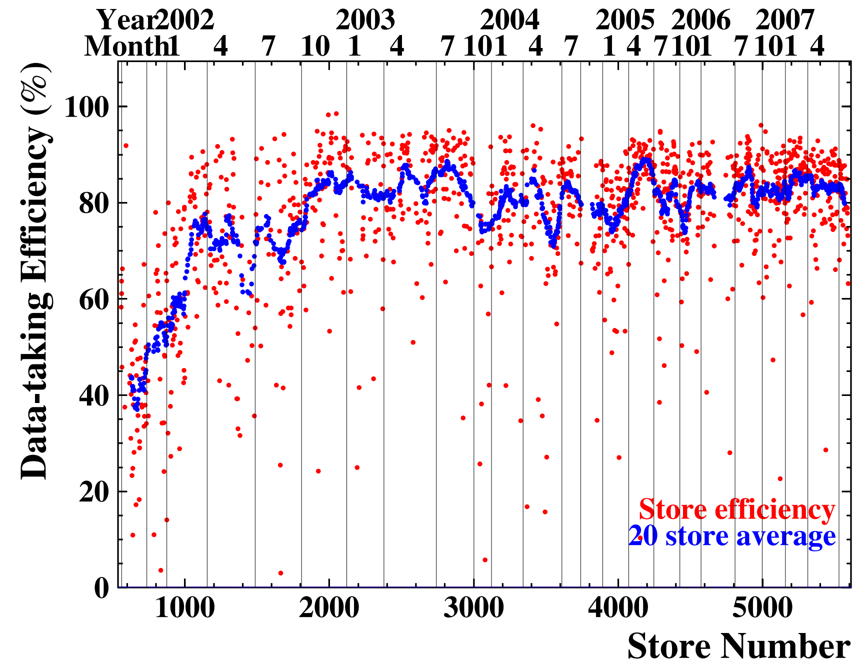
- $p\bar{p}$ (proton-antiproton) collisions at 1.96 TeV center of mass energy.
- Collisions every $396\ ns$.
- Two collison points: **CDF and** $\boldsymbol{D\text{Ø}}$**.**
- Run I (1992 - 1996): Top quark was discovered
- Run II (2001 - nowadays): top quark and W mass, single top and ZZ production evidence and B_s mixing.
- Now, It is time for Higgs.

Tevatron Performance

TOTAL LUMI DELIVERED / STORED



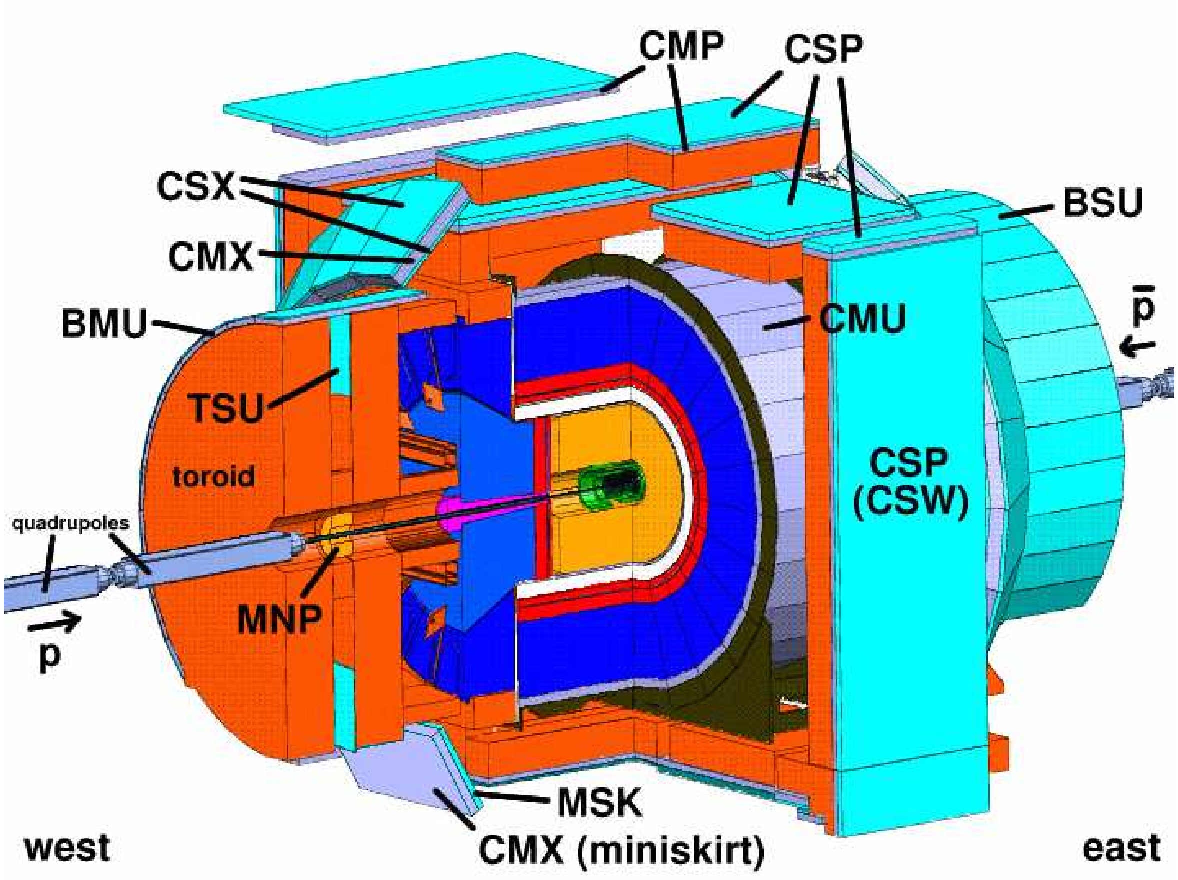
DATA TAKING EFFICIENCY



- $\sim$ 3.2 fb^{-1} delivered ($\sim$ 2.8 fb^{-1} recorded).
- Highest instantaneous luminosity $\sim 3\times10^{32}$ cm^{-2}s^{-1}.
- $N_{events} = L \cdot \sigma$

CDF Detector (Collider Detector at Fermilab)

- General purpose particle detector with cylindrical simmetry.
- 3 subsystems: tracking (inside a $1.4\,T$ solenoidal magnetic field), calorimetry and muons systems
- For Higgs physics the full detector is needed.



Motivation

- The Higgs boson is the last remaining Standard Model (SM) particle to be discovered.

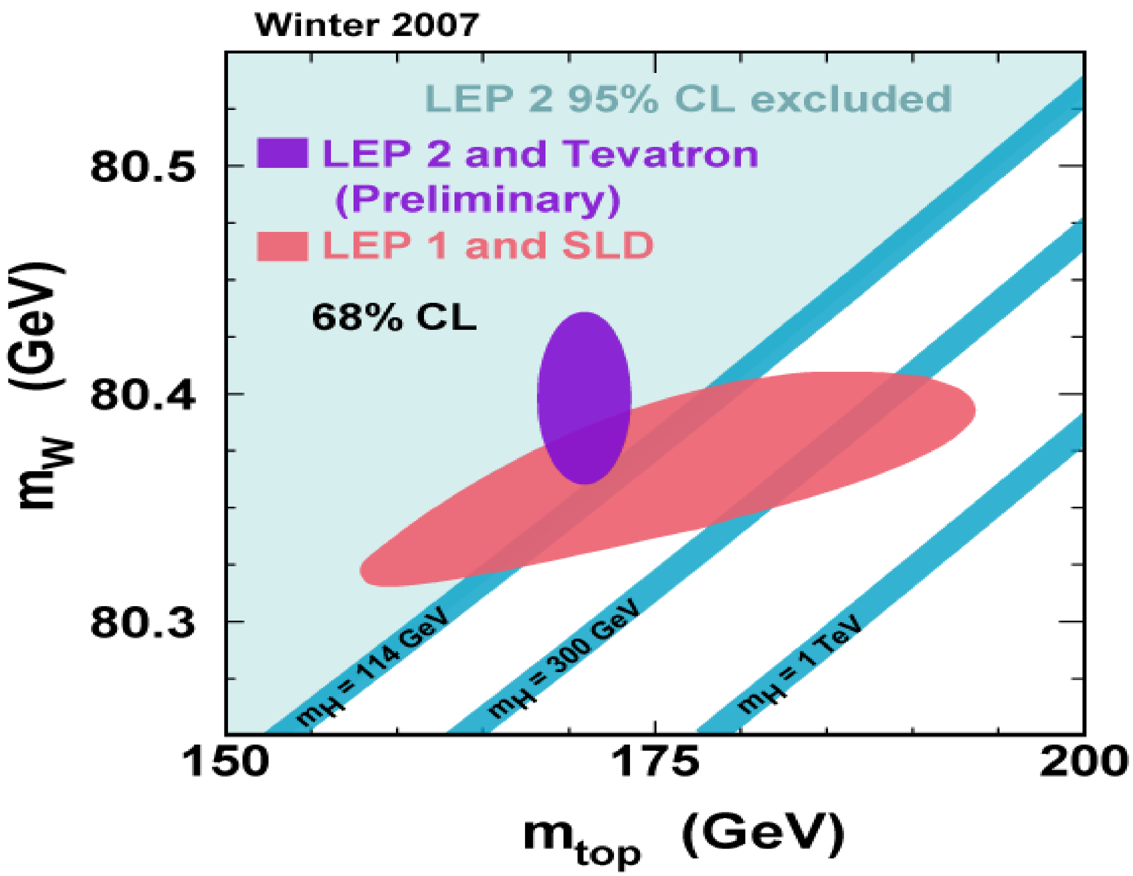
- Direct limit for LEP2:

  $m_H > 114.4$ GeV/c^2 at 95% CL.

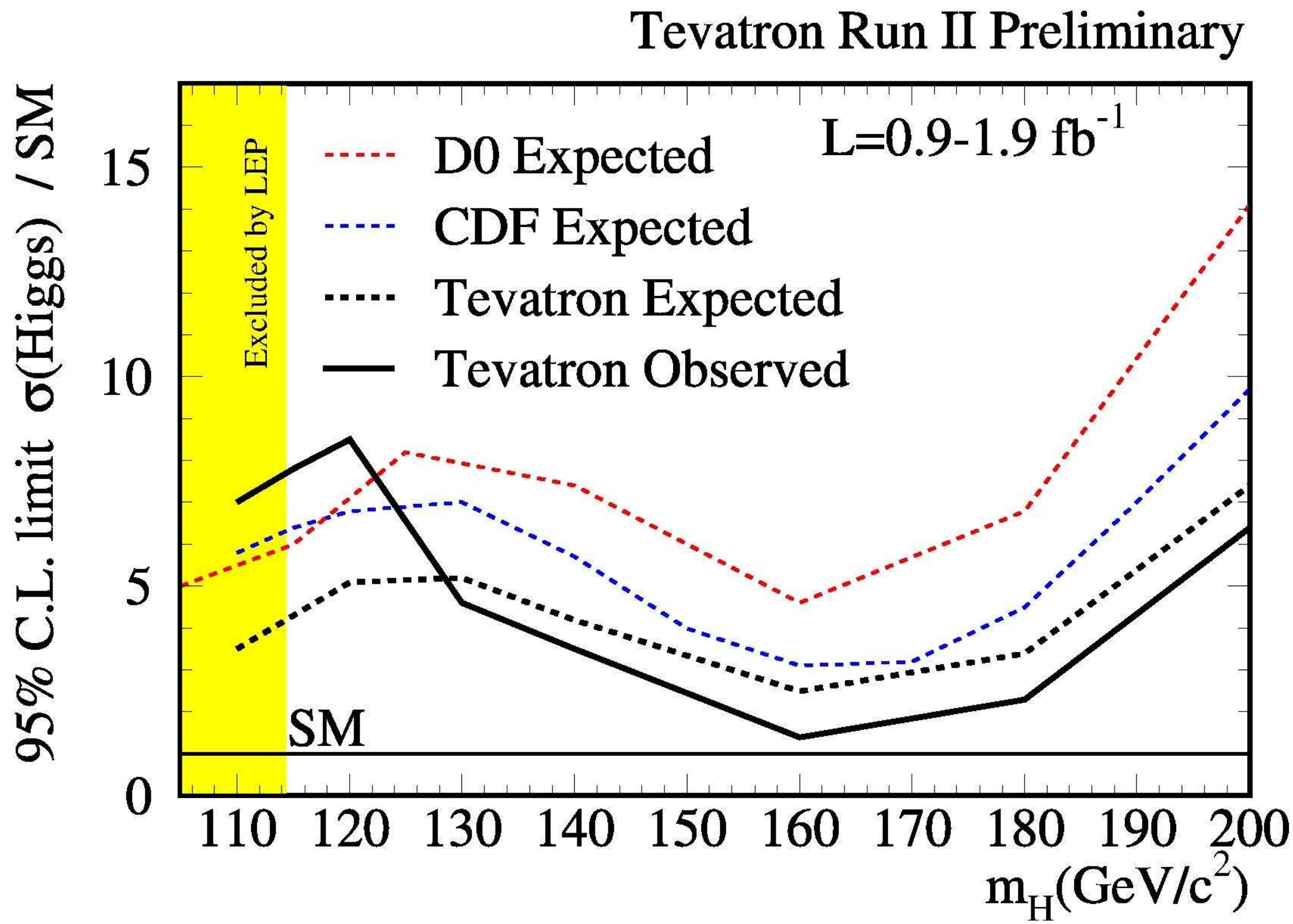
- Considering the new W and top mass measurements

  $m_H < 144.4$ GeV/c^2 at 95% CL

- Light Higgs is prefered.



Current Situation at Tevatron



- *DØ* and CDF have established the search for the SM Higgs as one of their **highest priorities.**

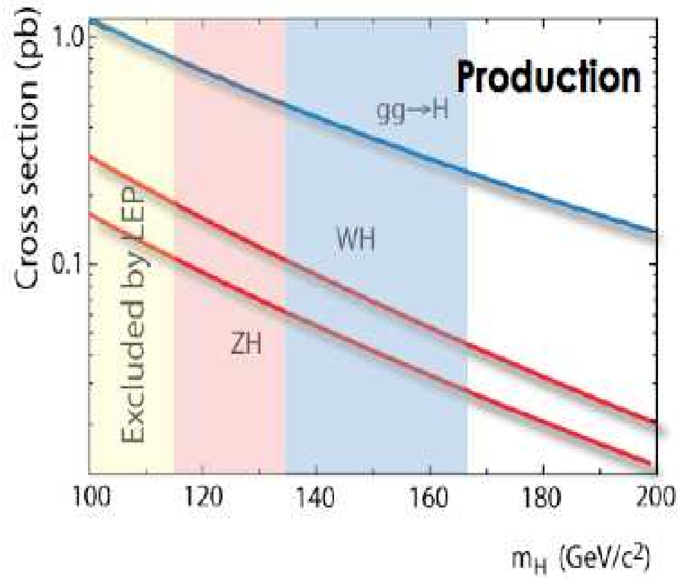
- No single improvement by itself will reach the sensitivity needed. All channels studied by both experiments must be combined, and as much data as possible must be analyzed.

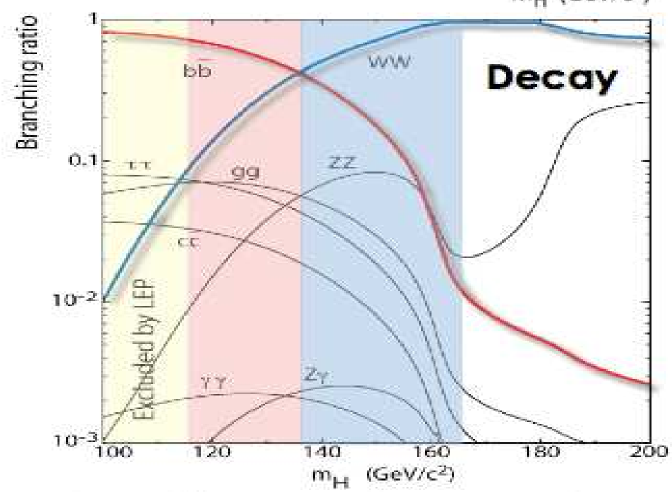
SM Higgs Physics: Production and Decay

- <u>Low mass:</u> $m_H < 135$ GeV
  - ♢ The most relevant production mechanism is the associated production together a vector boson (W or Z).
  - ♢ The highest branching ratio decay channel is to $H \rightarrow b\bar{b}$.
  - ♢ The main backgrounds are $Wb\bar{b}$, $t\bar{t}$, single top, $Z\tau\tau$ and dibosons.

- <u>High mass:</u> 135$< m_H <$200 GeV
  - ♢ Production mechanism $gg \rightarrow H$
  - ♢ The predominant decay channel is to $H \rightarrow WW$.
  - ♢ The main backgrounds are dibosons, Drell-Yan, $t\bar{t}$ and single top.

0.8 - 0.2 pb for $\boldsymbol{gg \rightarrow H}$
0.2 - 0.03 pb for $\boldsymbol{WH}$
0.1 - 0.01 pb for $\boldsymbol{ZH}$





Background Estimate

Top/EWK (WW/WZ/Z→ττ, ttbar, single t)

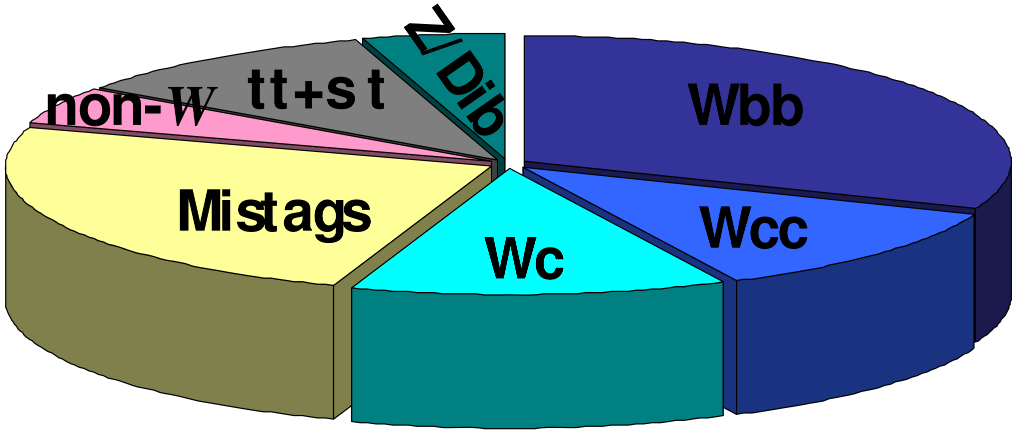
- MC normalized to theoretical cross-section

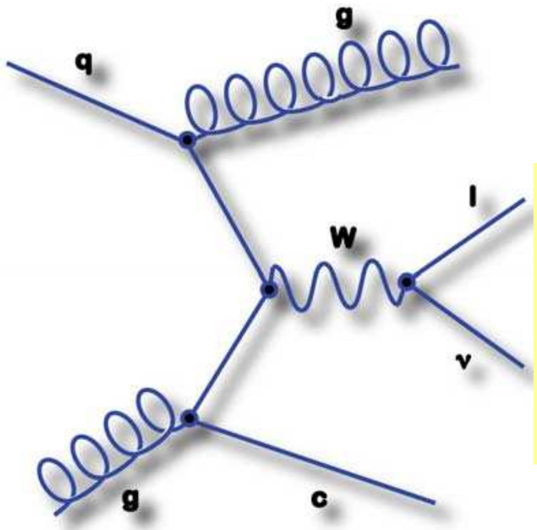
W+HF jets (Wbb/Wcc/Wc)

- W+jets normalization from data and heavy flavor (HF) fractions from ALPGEN Monte Carlo, calibrated in generic multijet data

Non-*W (QCD)*

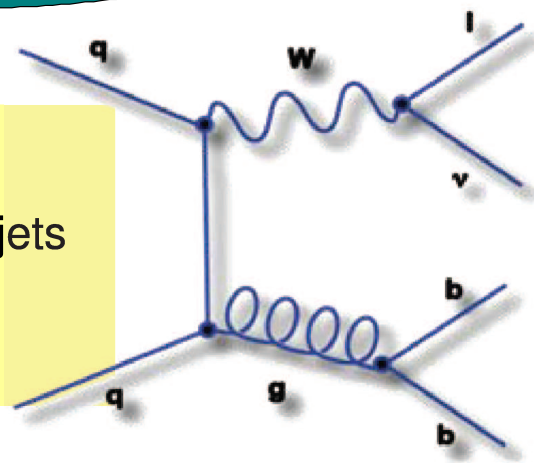
- Multijet events with semileptonic *b*-decays or mismeasured jets
- Fit low missing E_T data and extrapolate into signal region





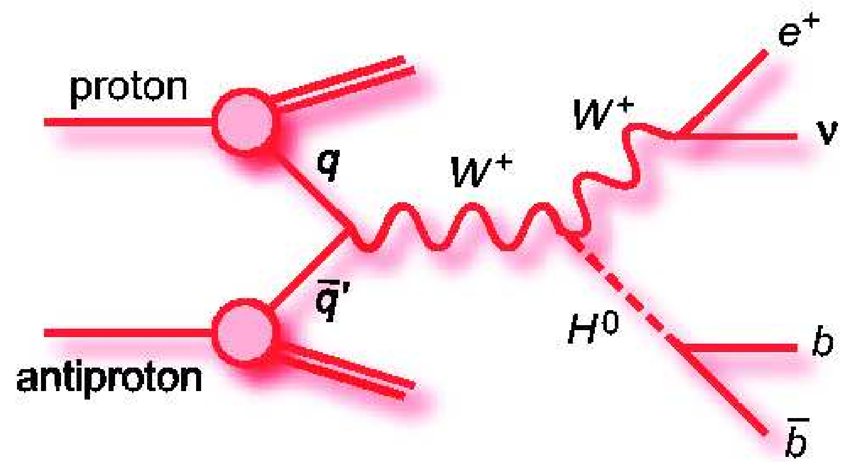
Mistags (W+2jets)

- Falsely tagged light quark or gluon jets
- Mistag probability parameterization obtained from inclusive jet data

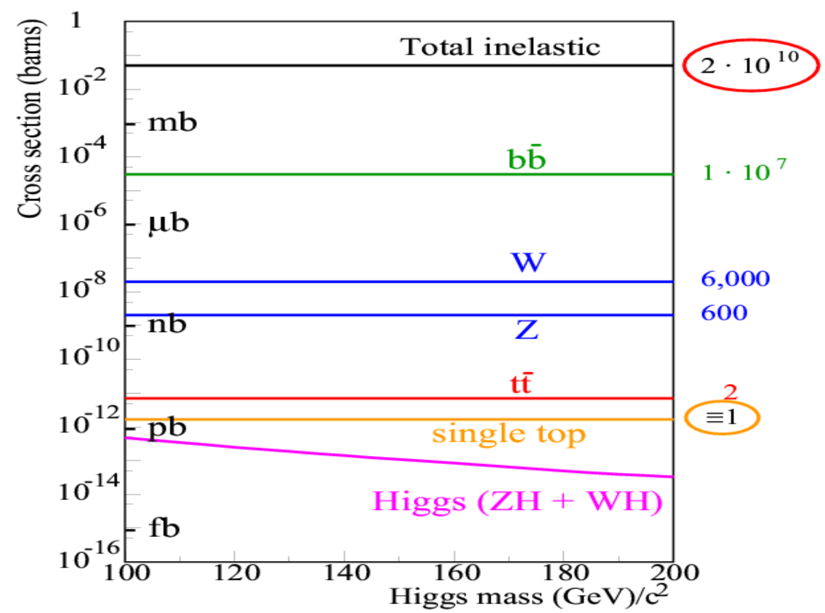


Event Selection

- Event Selection:
  - ◇ High p_T isolated lepton (e/μ):
    $p_T > 20$ GeV.
  - ◇ High missing transverse energy:
    $\not{E}_T > 25$ GeV.
  - ◇ Two jets with:
    - ⋆ Transverse energy:
      E$_T > 20$ GeV.
    - ⋆ Pseudorapidity ($\eta \equiv -ln\ tan(\frac{\theta}{2})$):
      $|\eta| < 2.8$
  - ◇ At least one jet identified as b-jet.



Very challenging!!!

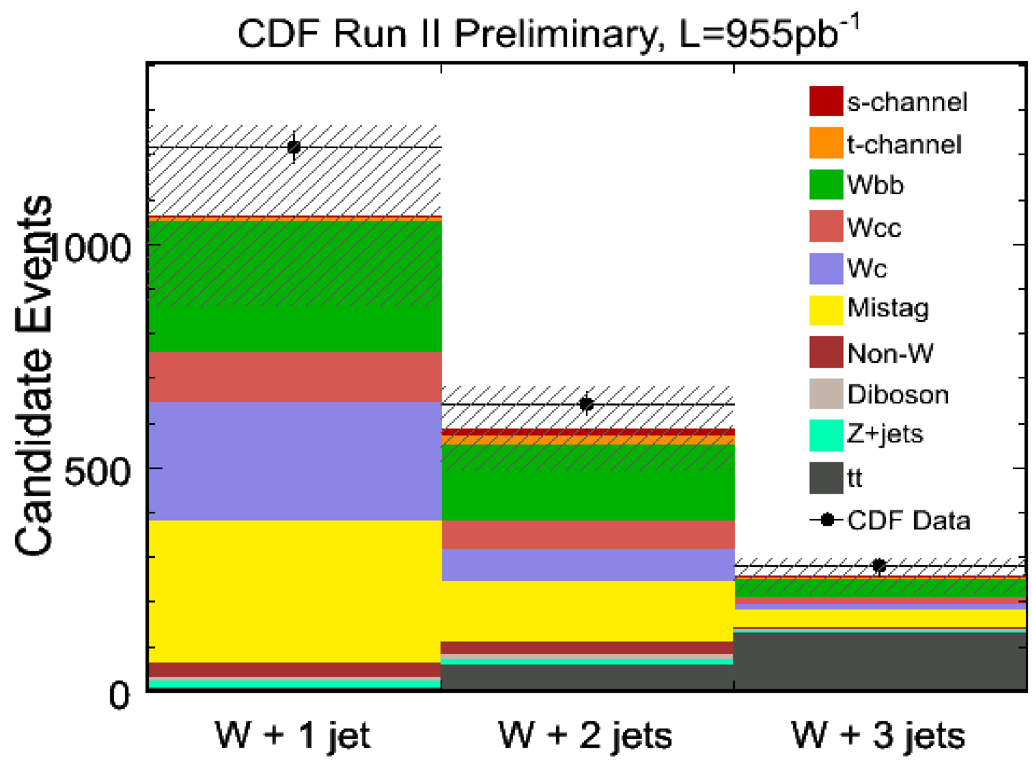


Sophysticated Tools Needed

- Signal is much smaller than background.

Signal hidden behind background uncertainty!

◇ Counting experiment are not possible ⇒ need sophysticated tools to isolate regions with high signal purity.



- **We use a Matrix Element (ME) Technique to calculate event probabilities for the signal and the background (bkg) hypothesis.**

Matrix Element Method

- Start from Fermi's Golden rule:

$$P_{evt} = \frac{d\sigma}{\sigma} = \frac{1}{\sigma}|M|^2 d\Phi$$

- But we need to consider:
  - ◇ Parton distribution functions (PDFs): interactions are initiated by partons inside the p and $\bar{p}$.
  - ◇ Neutrinos in the final state are not identified directly.
  - ◇ The energy resolution of the detector can not be ignored.
- Sum over all posible particle variables (y) leading to the observed variables (x).

$$P_{evt} = \frac{1}{\sigma}\int d\sigma(y) dq_1 dq_2 f(x_1) f(x_2) W(y,x)$$

- $f(x_i)$ are the PDFs with $xi = \frac{E_{q_i}}{E_{beam}}$ and $W(y,x)$ is the transfer function (TF).
- The transfer function (TF) is the probability of measuring x when y was produced.

Transfer Function

- The transfer function is given by:

$$W(y,x) = \delta^3(p_l^y - p_l^x)\Pi_{i=1}^2 \delta^2(\Omega_i^y - \Omega_i^x)\Pi_{j=1}^2 W_{jet}(E_{parton_j}, E_{jet_j})$$

- $''y''$ represents all final state particle momenta at particle level and $''x''$ represents the measured momenta.

- p_l^y and p_l^x are the produced and measured lepton momenta.

- Ω_i^y and Ω_i^x are the produced quark and measured jet angles.

- E_{parton} and E_{jet} are the procuded quark and measured jet energies.

- Because the lepton and jet angles are well measured:

$$W(y,x) = \Pi_{j=1}^2 W_{jet}(E_{parton_j}, E_{jet_j})$$

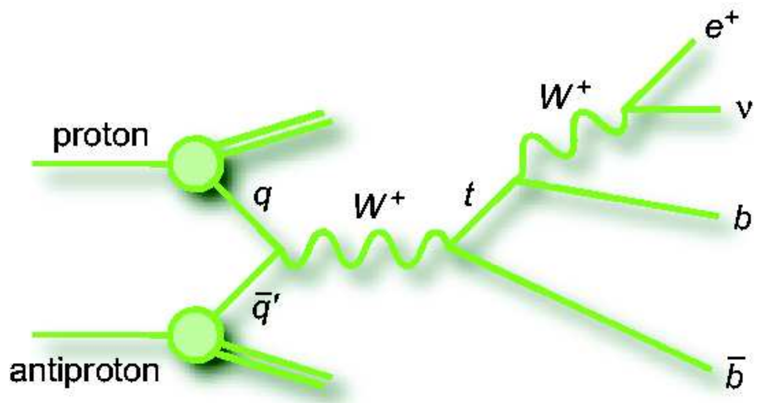
- The TF correct for jet energy, hadronization, detector effects,...

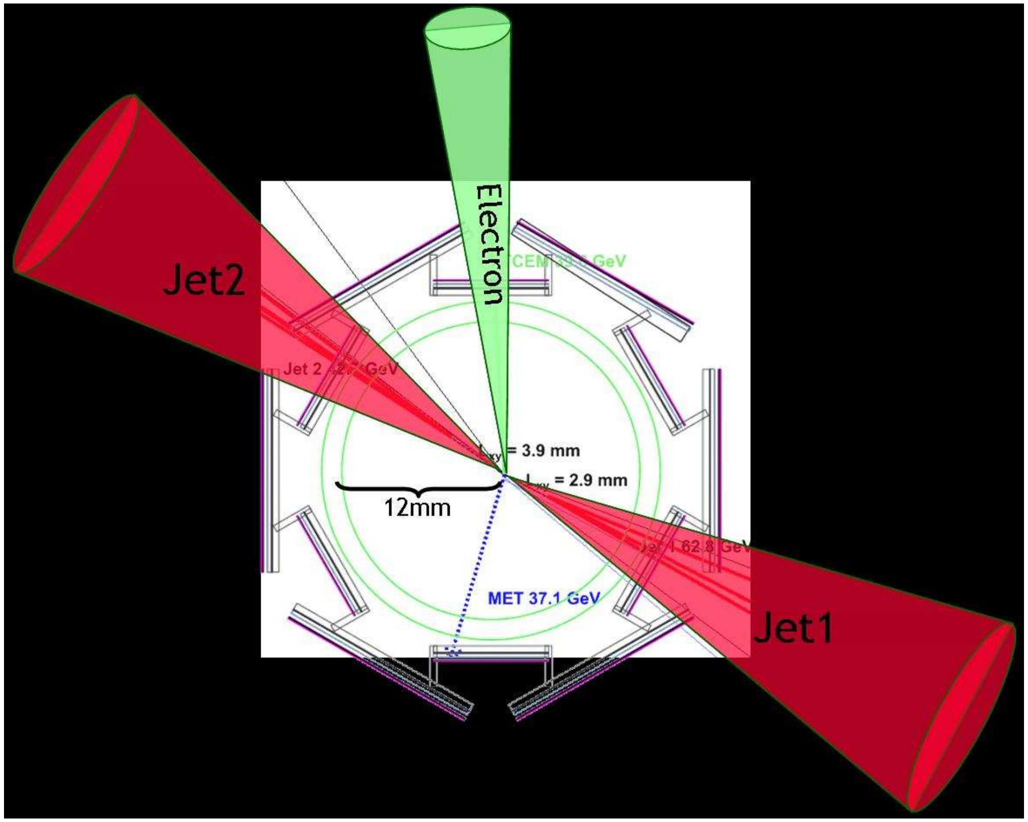
Application to the search of the Single Top

- s-channel single top has the same final state as $WH \rightarrow l\nu b\bar{b}$

- Benchmark for $WH \rightarrow l\nu b\bar{b}$

$single\ top\ (s-channel)$





- The complete application of the ME method to this final state has shown an evidence single top process.

- Transition from top physics to higgs physics.

Single Top Event Selection and Kinematic Variables

- Same event selection as $WH \rightarrow l\nu b\bar{b}$:

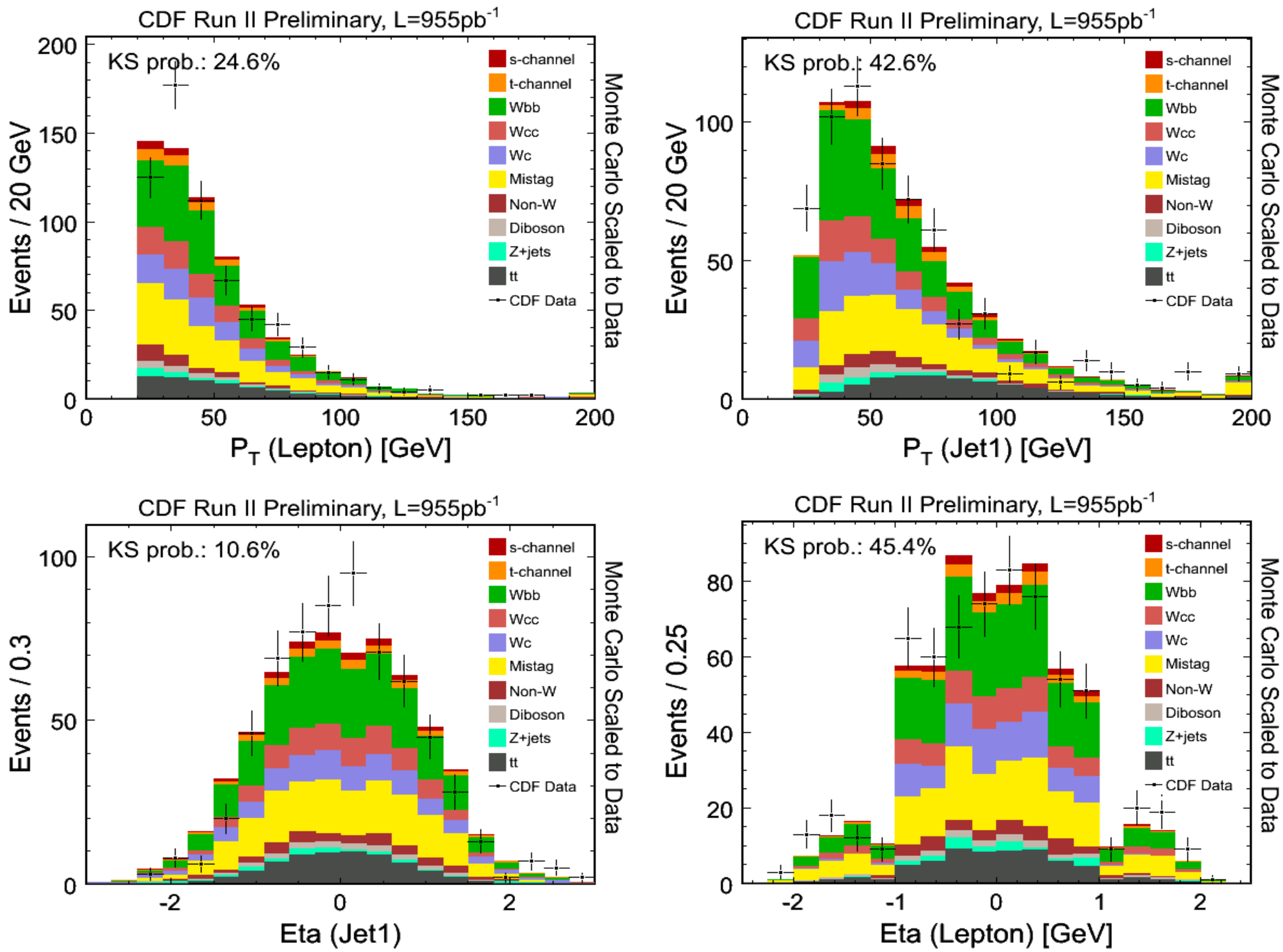
◇ One Lepton
$p_T > 20$ GeV,
$|\eta_{e(m)}| < 2.0(1.0)$

◇ $\not{E}_T > 25$ GeV.

◇ Two jets
$E_T > 20$ GeV,
$|\eta| < 2.8$

◇ At least one jet identified as b-jet.

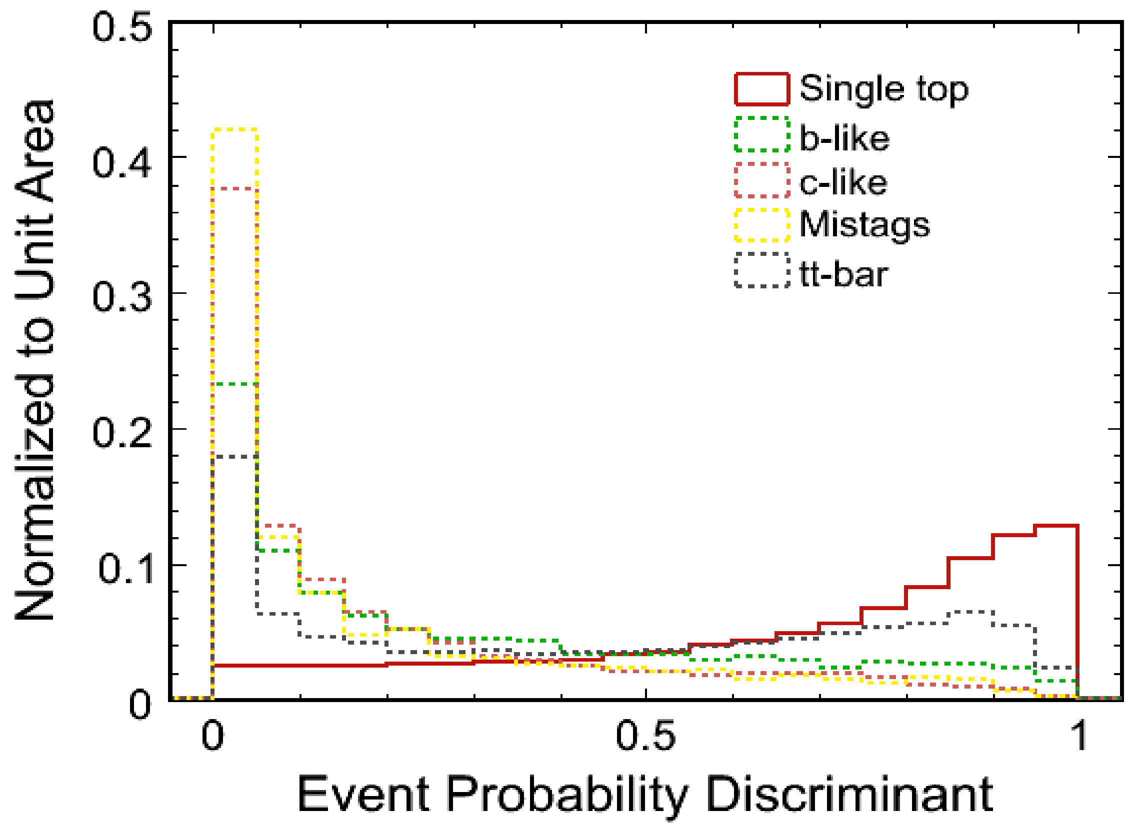
◇ This kinematic variables are the input variables for the event probabilities.



Event Probability Discriminant

- Define ratio of probabilities, obtained with the ME, as **E**vent **P**robability **D**iscriminant (EPD):

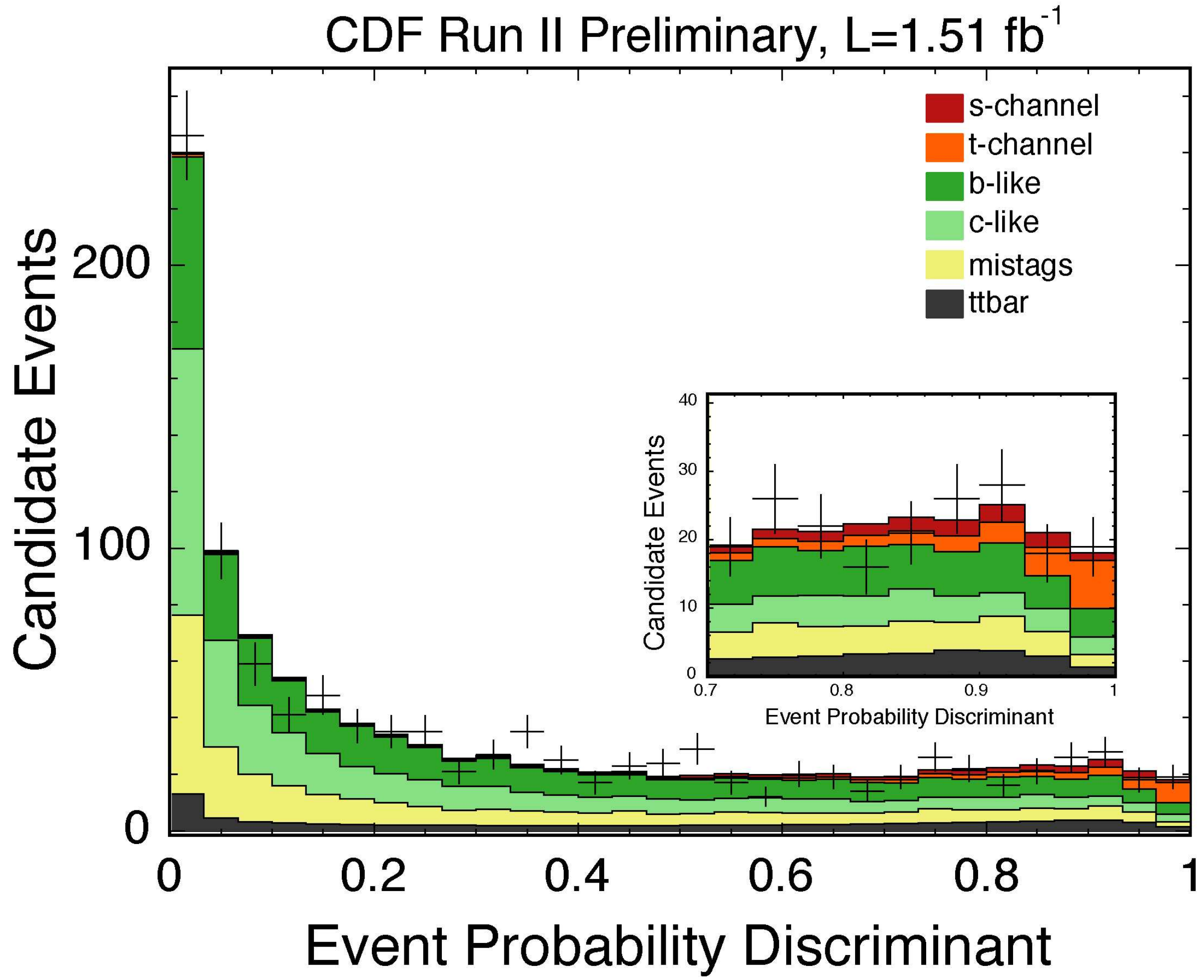
$$EPD = \frac{b\ P_{singletop}}{b\ P_{singletop} + b\ P_{Wbb} + (1-b)\ P_{Wcc} + (1-b)\ P_{Wcj}}$$



Binned Likelihood Fit

- Likelihood function:

$$L(\beta_1,...,\beta_5;\delta_1,...,\delta_{10}) = \Pi_{k=1}^{B} \frac{e^{-\mu_k} \cdot \mu_k^{n_k}}{n_k!} \cdot \Pi_{j=2}^{5} G(\beta_j|1,\Delta_j) \cdot \Pi_{i=1}^{10} G(\delta_i,0,1)$$

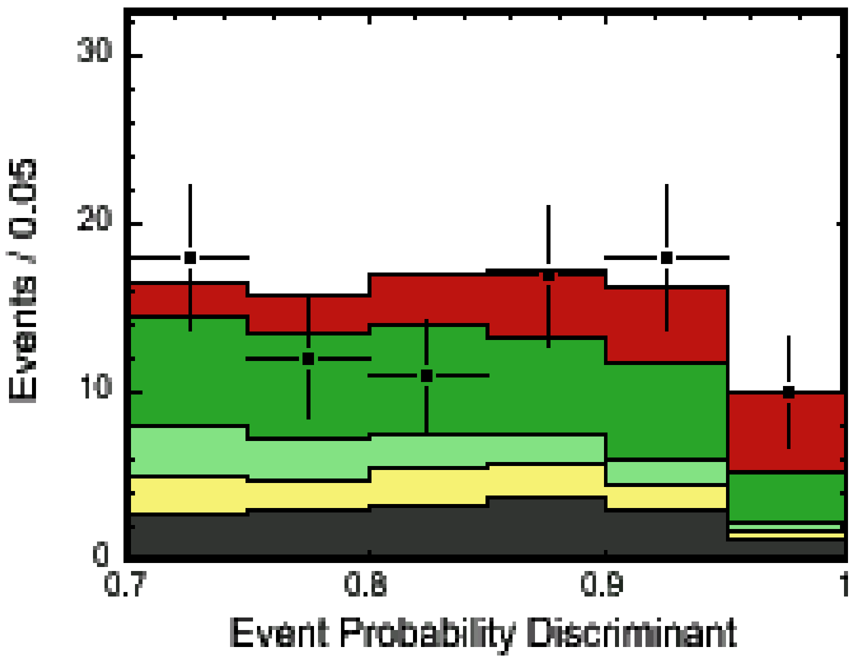


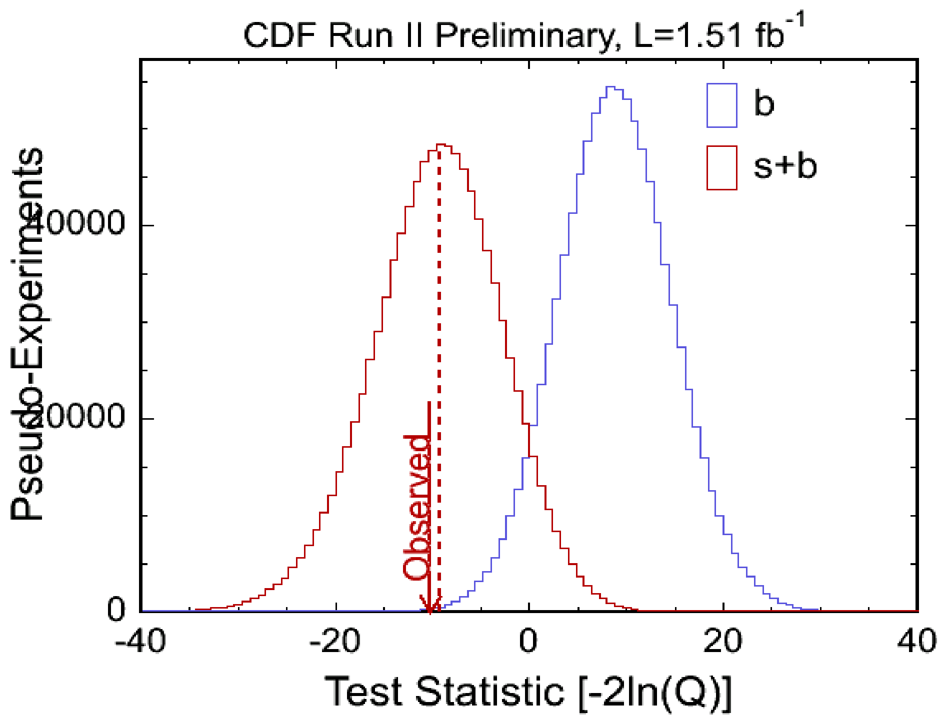
Hypothesis Test

- We use the CLs/CLb Method developed at LEP.
- Define Likelihood ratio test statistic ⇒

$$Q = \frac{L(data|s+b)}{L(data|b)}$$

- Most sensitive bins:





Expected sensitivity: 0.10% (3.1σ)

Observed sensitivity: 0.07% (3.2σ)

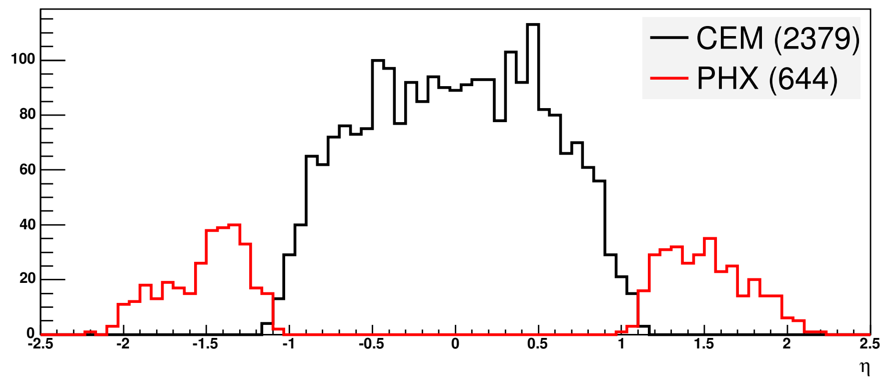
$WH \rightarrow l\nu b\bar{b}$

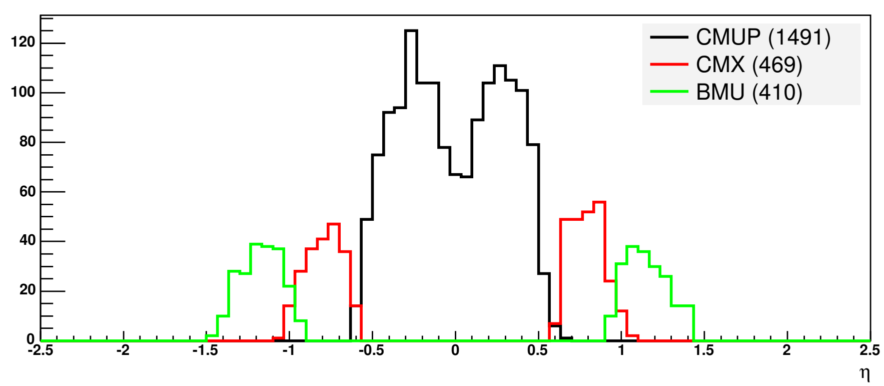
- Application of the ME method and improvements for WH search.
- Improvements to Event Selection:
  - ◊ Add new lepton categories.
  - ◊ Reduce the backgrounds by improving the identification of b-jets, using new btagging algorithms.
- Improvements to the ME method:
  - ◊ Add information to the TFs.
    - ⋆ Different jet cone sizes for better energy resolution.
- Study of the mass resolution of the $b\bar{b}$ system.
- Study the systematic uncertainties.
- Add as much data as possible.
- Extract the maximal sensitivity from the data.

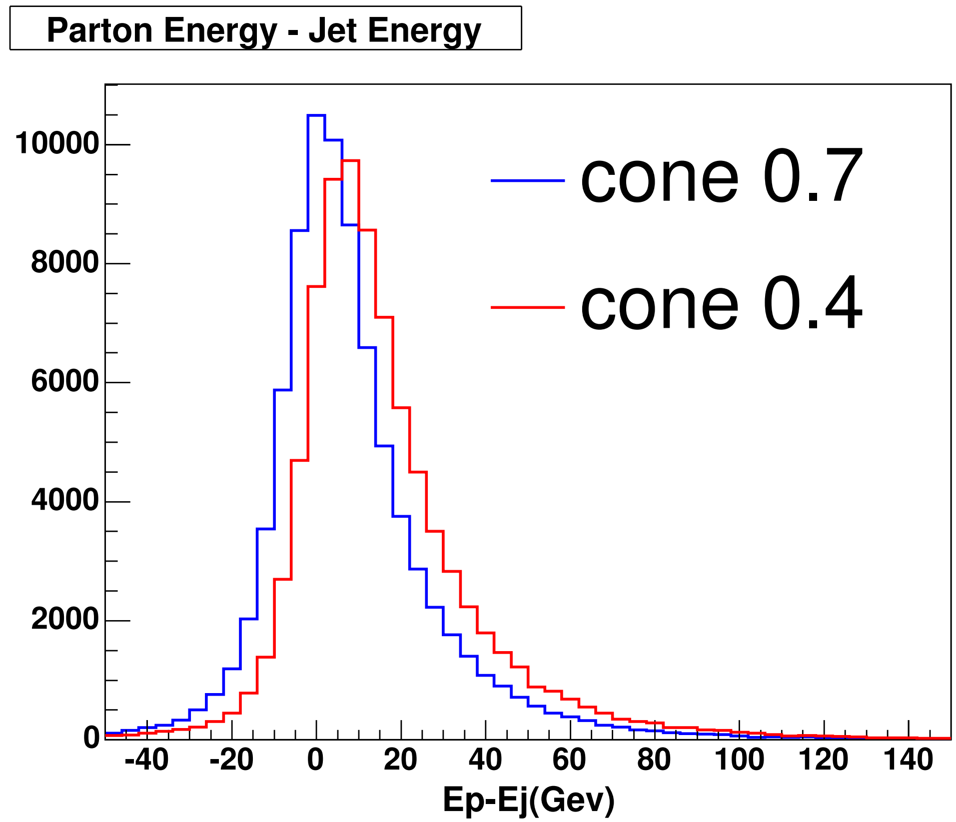
Improvements

- New lepton categories:
  - ♢ Electrons: CEM and PHX.
  - ♢ Muons: CMUP, CMX and BMU.

- Different cone size jets:
  - ♢ Jets of conesize 0.4
  - ♢ Jets of conesize 0.7







Conclusions

- Advanced analysis tools essential to establish small signals buried underneath large backgrounds.

- No single golden kinematic variable. Attempt to include all available kinematic information by using Matrix Element approach.

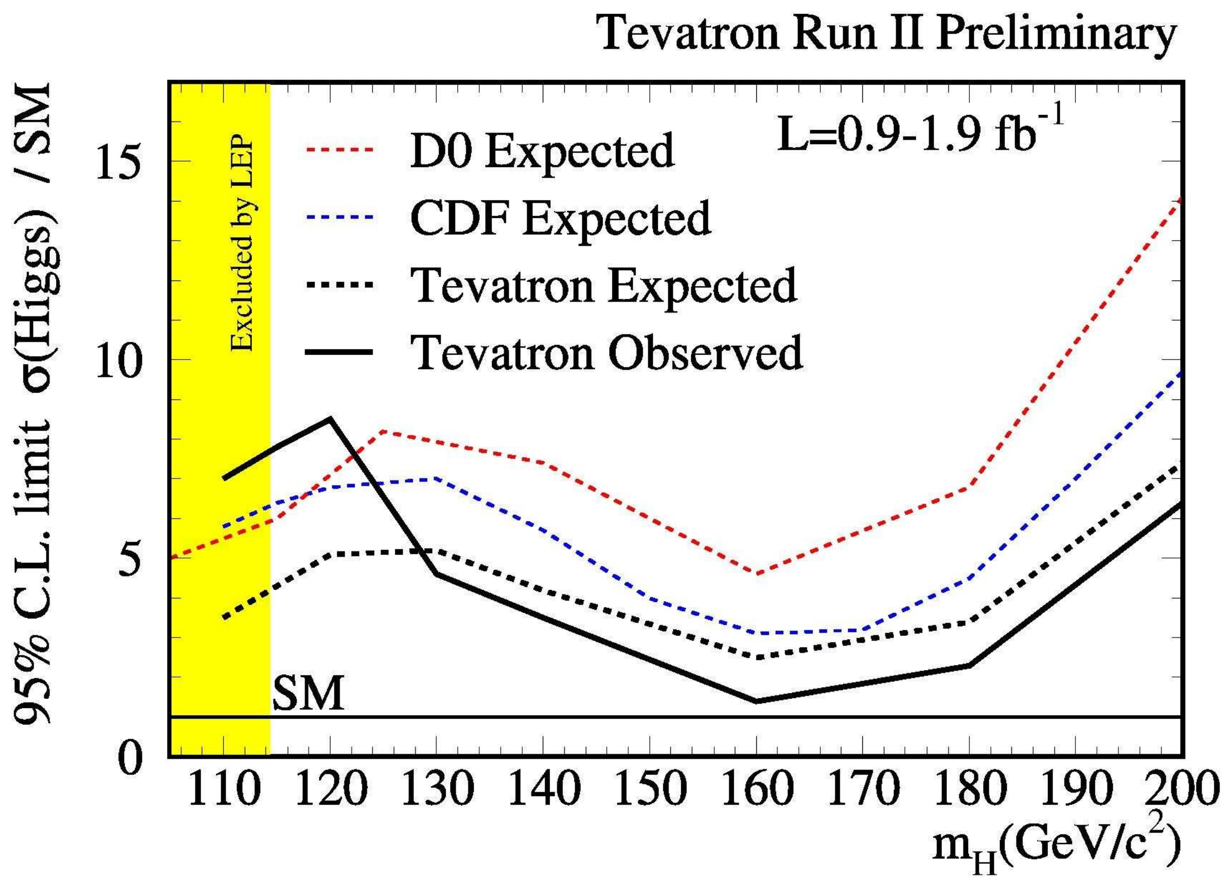
- Recent evidence for electroweak single top quark production at the Tevatron established by CDF and DØ experiment.

- Then, the Matrix Element Method has been validated by this evidence of the single top having the same final state as $WH \rightarrow l\nu b\bar{b}$

Conclusions

- Important milestone along the way to the Higgs!

  - ◇ Most of the tools needed for the WH full analysis are ready.
  - ◇ But several improvements, with respect to the single top analysis, are being studied.



Back Up

Fermi's Golden Rule

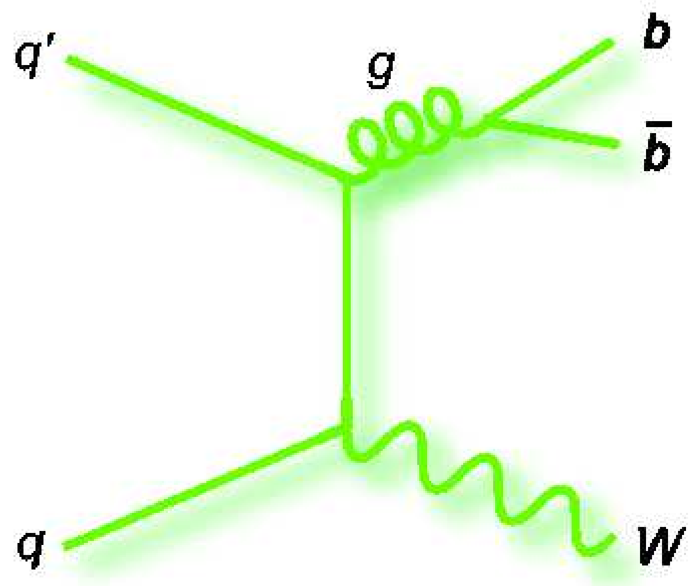
- And the Fermi's golden rule tell us the differential cross-section for a given scattering process:

$$d\sigma = \frac{(2\pi)^4 |M|^2}{4\sqrt{(q_1 \cdot q_2) - m_{q_1}^2 m_{q_2}^2}} d\Phi_n(q_1 + q_2; p_1, ..., p_n)$$

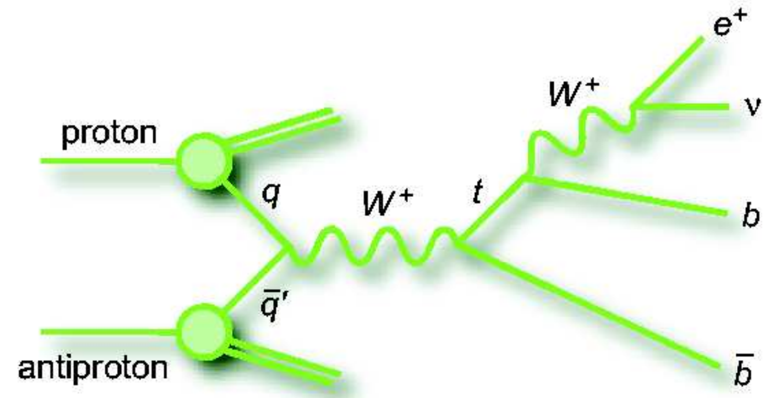
  - ◊ $|M|$ is the Lorentz invariant matrix element.
  - ◊ q_1, q_2 and m_{q_1}, m_{q_2} are the four momenta and masses of the incident particles.
  - ◊ $d\Phi_n$ is the n-body phace space.

Background Feyman Diagrams and Cross Sections

$W + jets$

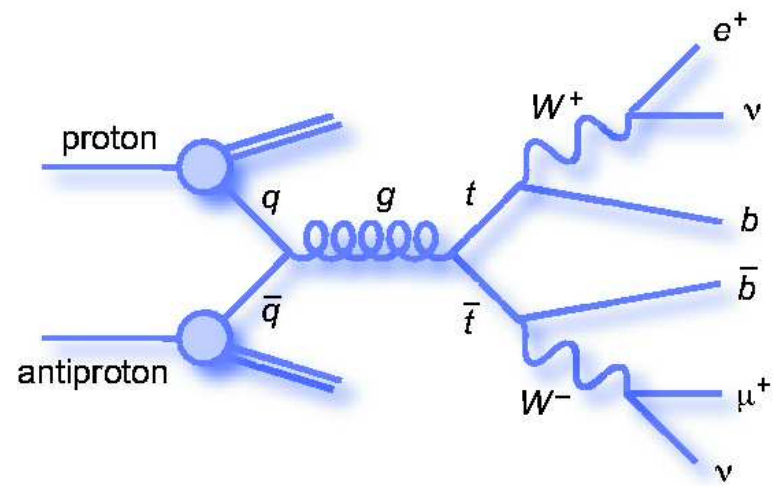


$single\ top\ (s - channel)$



Process	Cross Section (pb)
WH	1 - 0.01
Single Top W^* (s-channel)	0.88 ± 0.11
Single Top $W - g$ (t-channel)	1.98 ± 0.25
ZZ	1.58 ± 0.02
WZ	3.96 ± 0.06
WW	13.25 ± 0.25
$t\bar{t}$	8.9 ± 1.0
$Z \to \tau^+\tau^-$	254.3 ± 5.4

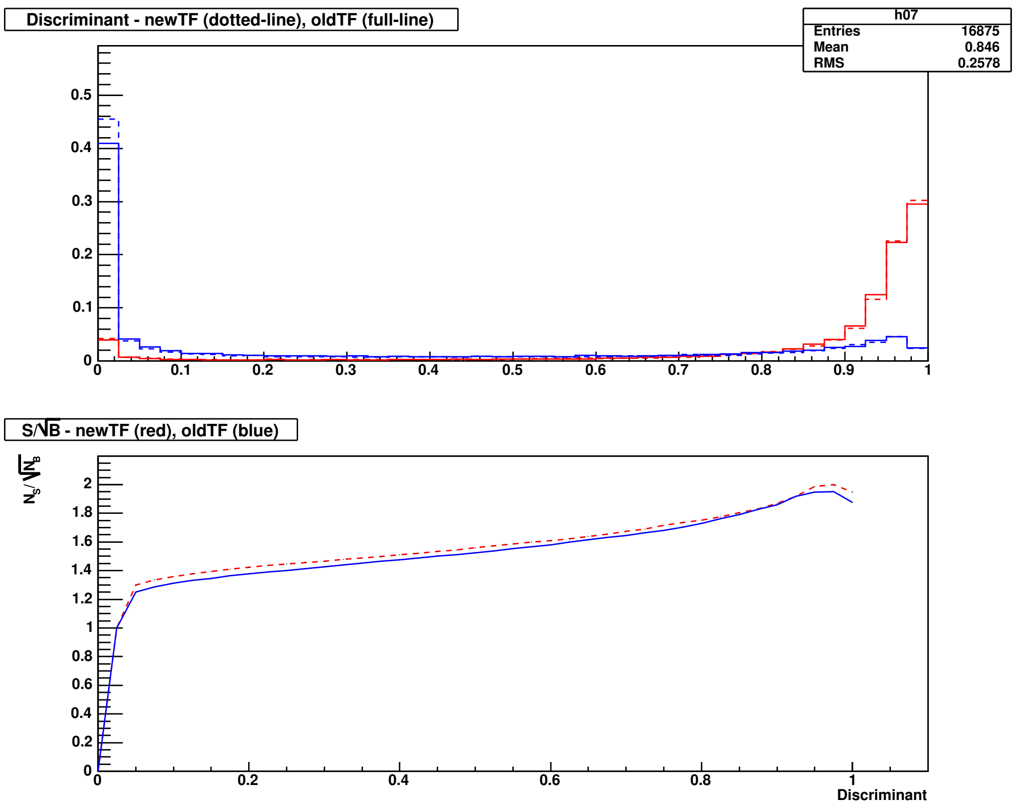
$t\bar{t}$



WH Event Probability Discriminant

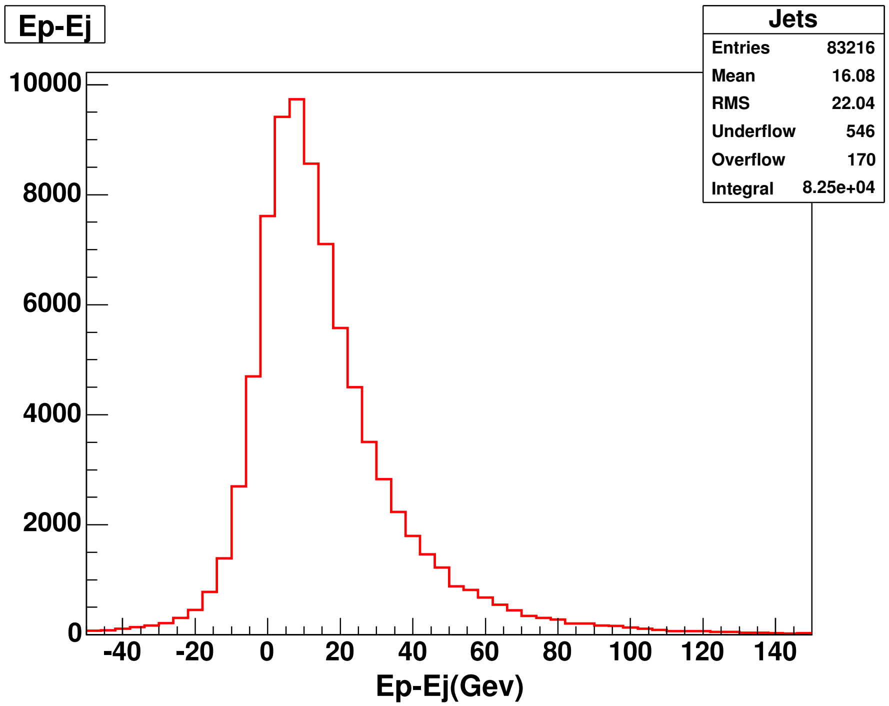
- Definition of the discriminant: Event Probability Discriminant.

$$EPD = \frac{P_{evt}(signal)}{P_{evt}(signal)+P_{evt}(bkg)}$$



- The blue lines are the background and the red ones are the signal.
- The dotted line is the new TF and the solid line is the old TF.
- For the bottom plot, the red line is the new TF and the blue line is the old TF.

Transfer Function for jet energies



- Mapping between parton and jet energies: $\delta_E = E_{parton} - E_{jet}$
- We parameterize the δ_E distribution as a sum of two Gaussian functions:
  - ◊ One to account the peak.
  - ◊ The other to account the asymmetric tail.

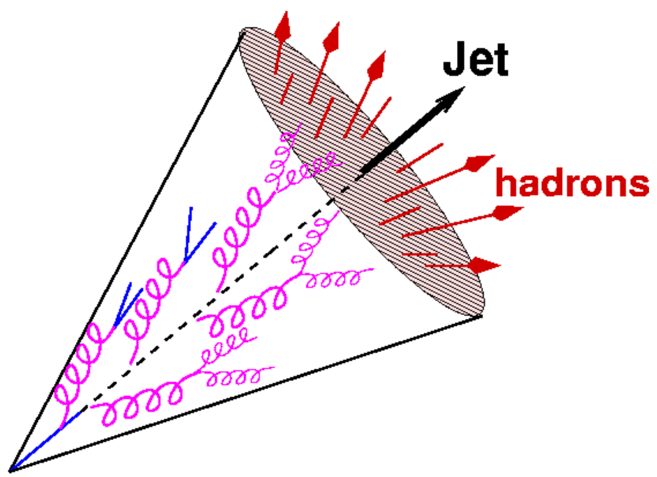
- Transfer Function (TF):

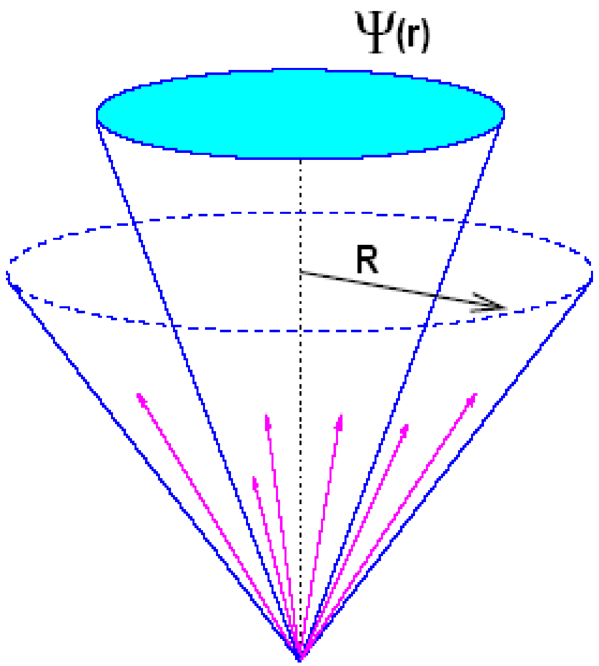
$$W_{jet}(E_{parton}, E_{jet}) = \frac{1}{\sqrt{2\pi}(p_2+p_3p_5)}(exp\frac{-(\delta_E-p_1)^2}{2p_2^2} + p_3 \cdot exp\frac{-(\delta_E-p_4)^2}{2p_5^2})$$

Where $p_i = a_i + b_i E_{parton}$. A total of 10 parameters $(a_1, b_1, ..., a_5, b_5)$ are required to specify $W_{jet}(E_{parton}, E_{jet})$.

Transfer Function Improvements

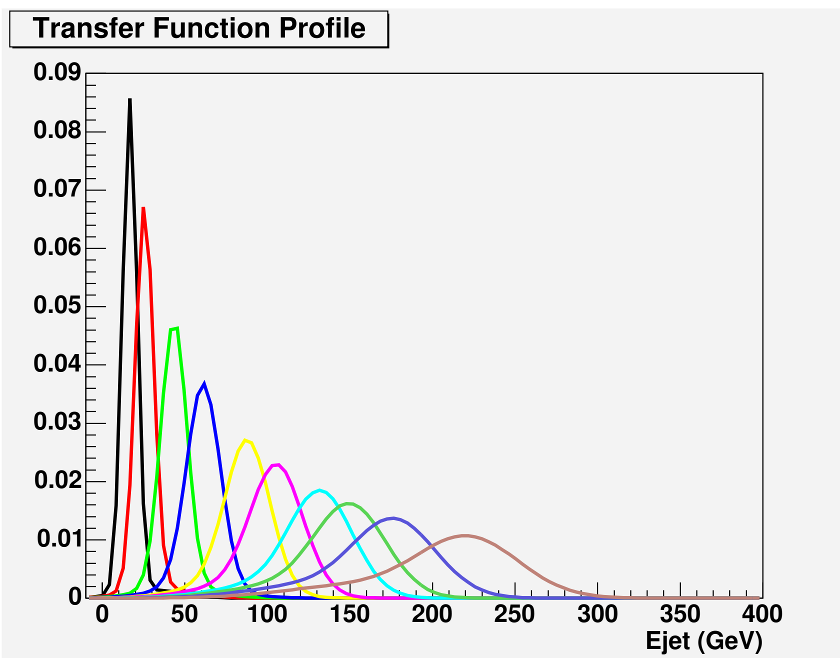
- We are adding more information to the mapping between partons and jets:
  - ◇ Jets of 0.7 conesize.
  - ◇ Different η regions.
  - ◇ SLT
  - ◇ SumE studies.
  - ◇ btagging variables: JetProb and SecVtx.



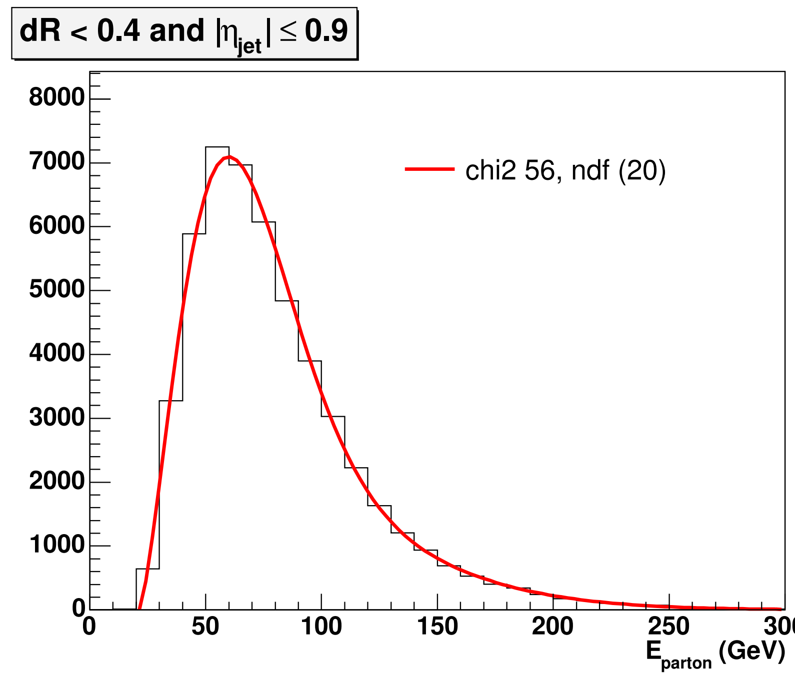


Transfer Function in parton energy bins

- Jets of 0.4 conesize, ΔR(jet, parton)$<$0.4 and $|\eta_{jet}|$ $<$0.9:
- Different parton energies (20,30,50,70,100,120,150,170,200,250)GeV.
- Parton Energy distribution (n(E_{parton})) fitted with two gaussians and one exponential.



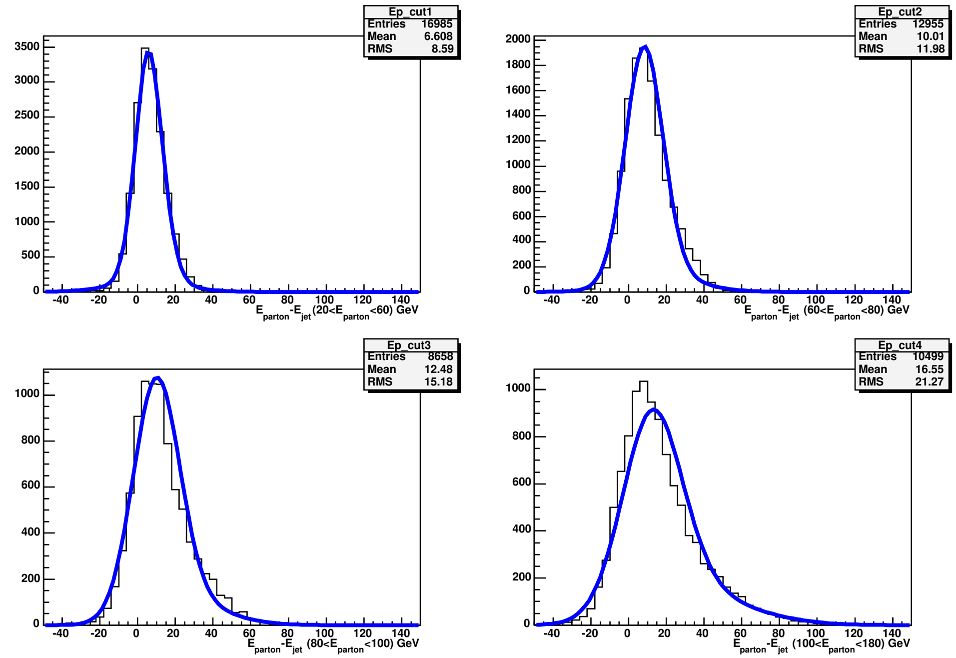
TF in 2-D



E_{parton} distribution

Test the Transfer Function

- The performance of the parameterization is shown in the figure.
- The δ_E distribution is compared with the prediction from the transfer function.
  - ◇ The histogram corresponds with the δ_E distribution.
  - ◇ The solid line is the convolution of the transfer function with the parton energy spectrum.



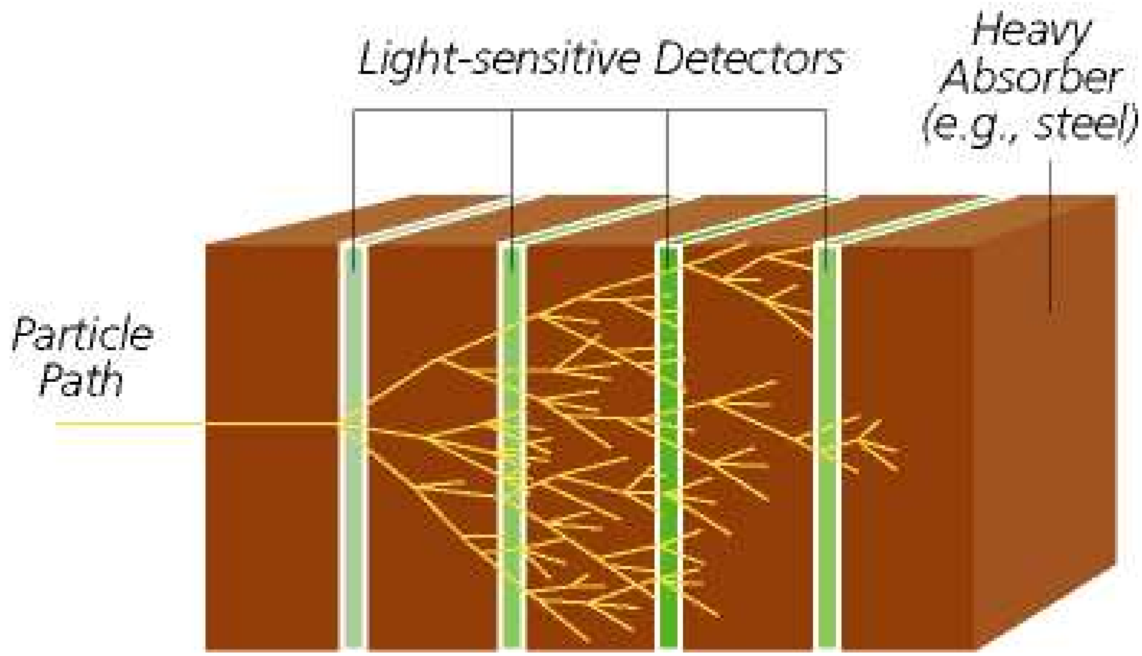
$$H(E_{parton}, E_{jet}) = \int_{E^1_{parton}}^{E^2_{parton}} n(E_{parton}) \cdot W(E_{parton} - E_{jet}, E_{parton}) dE_{parton}$$

Calorimetry

- Scintillator based calorimeter: Scintillating detectors after absorbing material.

- As the particle goes through the absorbing material, it forms a shower of secondary particles.

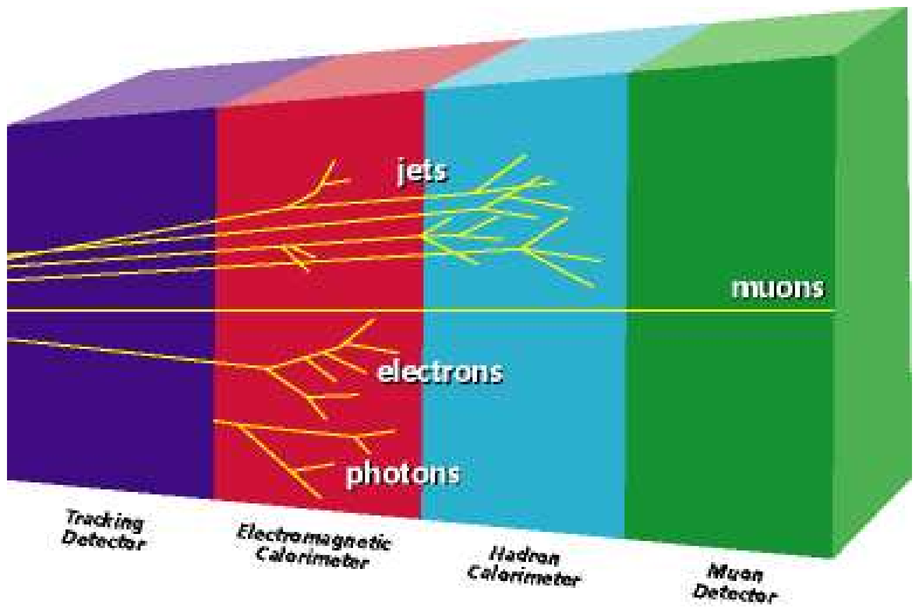
- The scintillators convert the energy into light which can be observed by light-sensitive detectors.



- The amount of light observed measures the energy of the particle.

Particle identification with calorimeter

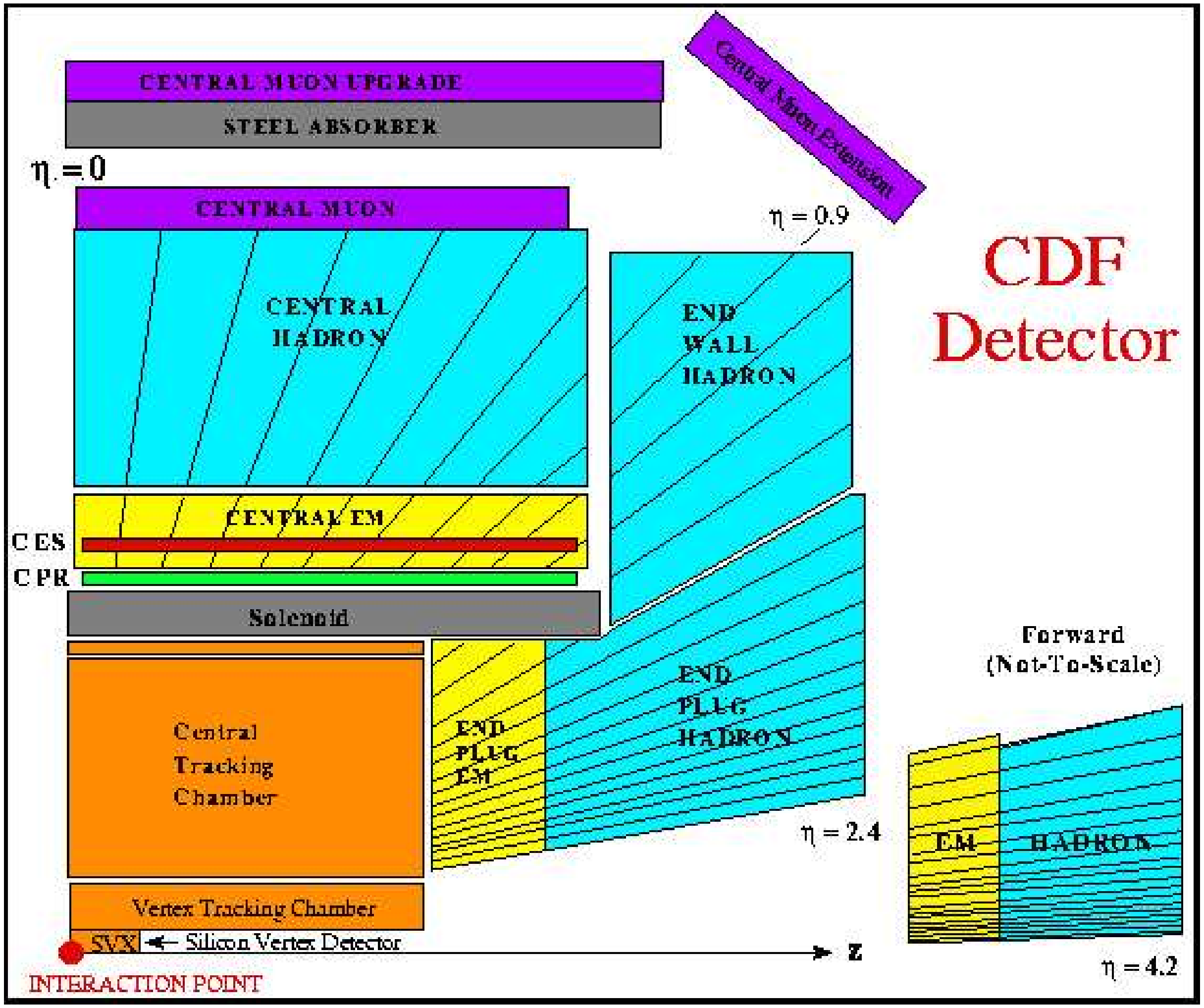
- In calorimeters different particles travel different distances before being absorbed.
- Photons and electrons lose energy very quickly and stop in the electromagnetic calorimeter.
  - ◇ Photons don't leave signal in the tracking detector.
- Muons can pass through many cm of material before losing their energy.
- Jets from quarks reach the hadron calorimeter and form hadronic showers.



- The distance a particle travels in a calorimeter is used to identify the particle.

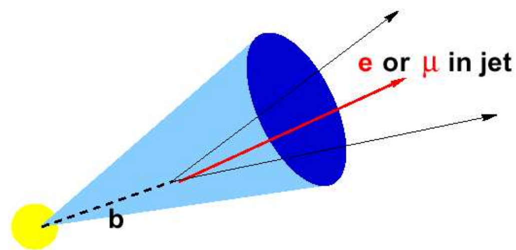
CDF calorimeter

- Electromagnetic (EM) and Hadronic (HADRON) calorimeters :
  - Lead for EM
  - Steel for HADRON
- Coverage:
  - $|\eta| < 3.6; \eta \equiv -ln\ tan(\frac{\theta}{2})$
  - $\phi < 2\pi$
- Regions:
  - Central: $|\eta|$ <1.1
  - Plug: 1.1< $|\eta|$ <2.1
  - Forward: 2.1< $|\eta|$ <3.6



Taggers

- Soft Lepton Tagger: looks for an energetic lepton inside a jet.



- $b \to \ell\nu c$ (BR $\sim$ 20%)
- $b \to c \to \ell\nu s$ (BR $\sim$ 20%)

- Identify a b-jet with different btagging algorithms: Secvtx, JetProb and combined.